Optically controlled graphene based terahertz modulator

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Abstract: A spectrally wide-band terahertz modulator based on monolayer graphene on germanium (GOG) was proposed. Utilizing a homemade THz-TDS (Terahertz-time domain spectroscopy) system, it was experimentally demonstrated that the THz modulator can be tuned by a 1 550 nm pump beam in a frequency range from 0.2 to 1.5 THz. The average transmittance of THz decreased from 40% to 22% when the pump power was increased to 250 mW, while the absorption coefficient averaged increased from 19 to 44 cm^{-1}. The maximum modulation depth of the GOG modulator can reach as high as 62% at 0.38 THz and in a frequency range from 0.2 to 0.7 THz, the modulation depth was over 50%. Compared with bare Ge, it was proved that the modulation performance can be moderately enhanced by introducing monolayer graphene. This novel optically controlled graphene based THz modulator provides a feasible method for terahertz applications in communication and imaging.

Key words: terahertz modulator; graphene; THz-TDS; optically-control
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基于石墨烯的光控太赫兹调制器

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摘 要: 研究了锗基单层石墨烯结构宽带光控太赫兹调制器。利用实验室搭建的太赫兹时域光谱系统,实验证明了在 1 550 nm 飞秒光泵浦下,该太赫兹调制器工作带宽为 0.2~1.5 THz。当泵浦光功率从 0 增加到 250 mW 时,该太赫兹波调制器的平均透过率从 40%下降到 22%,平均吸收系数从 19 cm^{-1} 增加到 44 cm^{-1},在 0.2~0.7 THz,调制深度均高于 50%,最大调制深度为 62%(0.38 THz)。实验结果表明,相比于纯锗基太赫兹调制器,单层石墨烯的引入能增强对太赫兹波的调制效果。

关键词: 太赫兹调制器; 石墨烯; THz-TDS; 光控

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0 Introduction

Terahertz (THz) science and technology have drawn great attention of researchers in various scientific research fields in recent years. A variety of prospective applications for THz radiations have been considered in communications [1], imaging [2], medical diagnostic[3], and material characterizations[4-5]. In order to improve the performances of Terahertz-related applications, intensive and persistent investigations of relevant devices such as modulators [6], switches[7], waveguides[8], and filters[9], which are capable of actively manipulating THz waves in a desired manner, are performed. In particular, active THz modulator has significant applications in wireless communication system and imaging due to its capability of tuning the amplitude or phase at will.

Great efforts have been made on active THz modulator with the advantages of wide bandwidth, large modulation depth, high modulation rate, and etc. In 2004, T. K. Ostmanna developed an electrically controlled THz modulator based on a two-dimensional electron gas structure, whose maximum modulation depth is 6%[10]. Chen et al. introduced a metamaterial structure into THz modulator in 2006[11], which has a modulation depth up to 50% with rate limited to kb/s. In 2010, H. T. Chen et al. proposed a split-ring resonator array made from high temperature superconducting films, which achieved efficient metamaterial resonance switching and frequency tuning by varying the temperature[12]. Based on nonlinear photonic crystals, H. M. Chen et al. simulated an optically-controlled THz modulator in 2011 with properties of high speed and compactness[13]. Very recently, 2D layered materials have been applied to THz modulators due to their unique electrical and optical properties. In 2012, B. S. Rodriguez et al. demonstrated a graphene-based electro-absorption modulator achieved an extraordinary modulation depth of 64% [14], while the modulation effect was limited to a narrow bandwidth around 0.62 THz. In 2015, an active graphene-silicon hybrid diode was developed by Q. Li et al, which obtained a modulation depth up to 83% of THz wave [15]. Graphene is a fascinating material for terahertz applications with its strengths in atomic thickness, fine tunability, and high kinetic inductance[16], which opens up a door in THz modulator.

Herein we present a spectrally wide-band THz modulator based on graphene on germanium (GOG) structure. Utilizing a homemade THz-TDS system, the characteristic of the THz modulator in the frequency range from 0.2 to 1.5 THz has been investigated. When the germanium substrate was excited by a 1 550 nm pump beam, significant augmented conductivity was observed due to the photon-excited free electrons and holes which could be considered as a special type of doping, i.e. photo doping. Moreover, the transmittance, refractive index and absorption coefficient of the substrate varied accordingly. It is found that compared with the bare germanium substrate, GOG has a stronger attenuation for THz radiation, which indicates that the modulation performance can be moderately enhanced by monolayer graphene fabricated on germanium substrate.

1 Sample fabrication

The structure of the proposed THz modulator is depicted in Fig.1(a), where a monolayer graphene was fabricated on the top of a p-type germanium substrate provided by UESTC. The substrate was 250±25 μm in thickness with a moderate resistivity of 3 Ω·m. Graphene was firstly grown on copper using chemical vapor deposition (CVD) and transferred by means of polymethyl methacrylate (PMMA) [17]. The Raman spectrum of the graphene on germanium substrate is presented in Fig.1 (b) and the excitation laser has a wavelength of 442 nm. It is found that the intensity of 2D band located at 2 650 cm^{-1} is two times larger than that of G-band while the intensity of D-band at 1 325 cm^{-1} is quite low, indicating an intact monolayer graphene existing on germanium substrate.

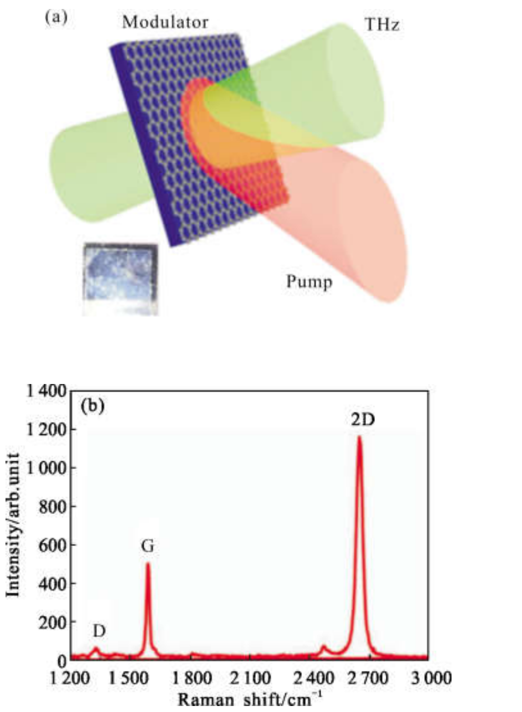

Fig.1 (a) Schematic diagram of optically controlled graphene based THz modulator. A monolayer graphene fabricated on Ge substrate was pumped by a 1 550 nm femtosecond laser (pink light). The inset picture at the left bottom of (a) is the photo of THz modulator. (b) Raman spectrum of graphene on Ge substrate

2 Experimental setup

The experimental investigations were carried out on a home-made THz time domain spectroscopy (TDS) system[18], as shown in Fig. 2. A pair of fiber coupled photoconductive antennas were used for the emission and the detection of THz radiation. The laser's central wavelength, pulse width, and repetition frequency were 1 550 nm, 84 fs, and 100 MHz, respectively. The light from laser source passed through a dispersion compensating fiber and a fiber-optic splitter and subsequently splitted into a pump beam and a probe beam. The probe beam was collimated by a GRIN (GRadient-INdex) lens when it exited from the fiber. After free space propagation in air, it was thereafter sent into another identical GRIN lens coupler attached with a fiber pigtail. The required temporal delay between the THz pulse and the probing laser pulse was produced by moving the GRIN lens coupler. Two off-axis parabolic mirrors were used to collect and collimate the THz beams, and each of them were mounted on guided rails and fixed with THz emitter and detector, respectively. Meanwhile another branch with power varied from 0 to 250 mW by neutral density filters illuminated the modulator. It should be noted that a focus lens should be select to ensure the pump beam completely overlap the THz spot.

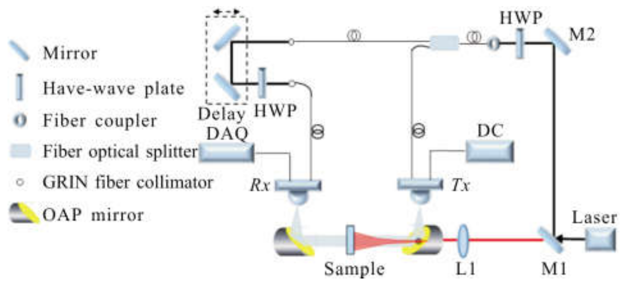

Fig.2 Schematic of the experimental setup for THz-TDS

The temporal waveform of the electric field of THz radiation after passing through the modulator can be obtained directly by THz-TDS. Using the fast Fourier transformation (FFT), both the phase and amplitude can be resolved in frequency domain. By comparing the cases with and without the modulator, the frequency dependent transmittance, refractive index and absorption coefficient can be calculated from the formula below[19].

The transmittance of THz radiation can be described as:

$$T(\omega)=\frac{P_{sam}}{P_{ref}} \tag{1}$$

where P_{sam} and P_{ref} are the transmitted THz power through the modulator and through the air without modulator respectively. The effective refractive index can be calculated as:

$$n_{sam}(\omega)=\frac{c}{\omega l}\cdot\Delta\varphi(\omega)+n_{ref} \tag{2}$$

where $\Delta\varphi=\varphi_{sam}-\varphi_{ref}$, which is the phase difference between the cases with and without modulator, l is the thickness of the modulator. The reference used in this work is air, thus $n_{ref}=n_{air}=1$. The absorption coefficient can be written as:

$$\alpha(\omega)=\frac{2}{l}\ln\left\{\frac{4n_{sam}(\omega)}{T(\omega)\cdot[n_{sam}(\omega)+n_{ref}]^2}\right\} \tag{3}$$

The parameters in Eq.(3) are the same as those mentioned above.

3 Results and discussions

The characteristic of the optically controlled graphene based THz modulator presented in this paper was experimentally investigated under an ambient temperature of 297 K and humidity of ~34%. The transmitted THz electric field of the bare Ge substrate and the GOG structure without photo doping are plotted in Fig.3(a). The signal amplitude of GOG is approximately identical with that of Ge substrate except for a negligible time delay (~0.33 ps), which means that graphene can be regarded transparent to THz waves without the optical pumping.

When GOG was illuminated by femtosecond laser pulses with a central wavelength of 1 550 nm, the modulation effect on THz radiation appeared. As is shown in Fig.3 (b), the electric field´s amplitude of THz wave decreases continuously as the power of the pump femtosecond laser gradually increases from 50 to 250 mW. The modulations of the transmittance, refractive index and absorption coefficient of GOG for THz radiation induced by the pump laser are shown in Fig.3 (c), 3 (d) and 3 (e), respectively. When the pump power was increased to 250 mW, in the frequency range of 0.2 –1.5 THz, the average transmittance of THz decreases from 40% to 19% which is mainly contributed by the increase of the absorption coefficient, and the coefficient averaged increases from 19 to 44 cm^{-1} when the pump power is increased to 250 mW. Besides, the refractive index reduced significantly at low frequency range. These phenomena can be attributed to the variation of conductivity of Ge substrate, which was induced by photon-generated carriers[20]. It should be noted that a thin film model was used to eliminate the oscillations due to Fabry-Perot effect in Fig.3(c), 3(d) and 3(e)[21].

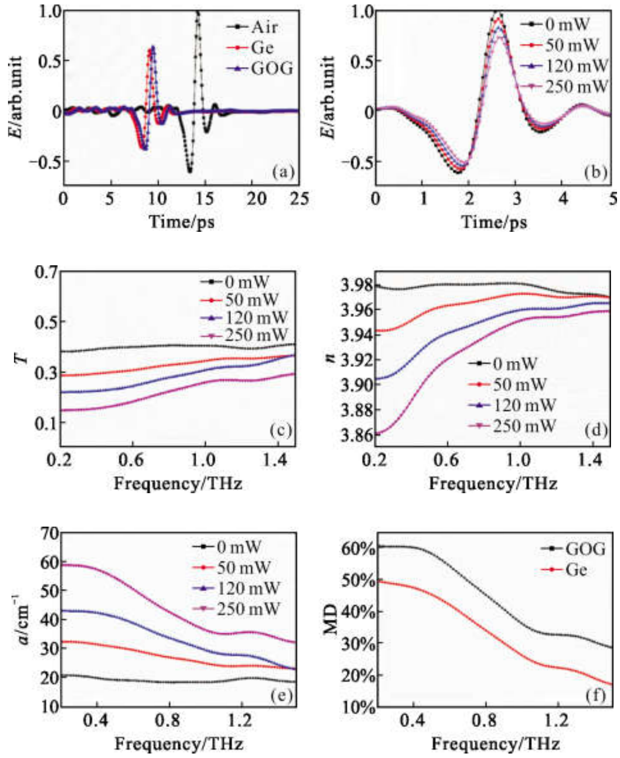

Fig.3 Normalized THz time domain signals of (a) reference (air), bare Ge substrate and GOG without pumping, (b) GOG under different pump power. Characteristics of GOG under different pump power in a frequency range from 0.2 to 1.5 THz, including (c) transmittance, (d) refractive index, (e) absorption coefficient. The frequency-dependent modulation depths of bare Ge and GOG pumped by femtosecond laser of 250 mW are shown in (f)

The modulation depth is a commonly-used parameter to evaluate a modulator, which can be defined as $\mathrm{MD}=|(T_p-T_0)/T_0|$, where T_p and T_0 are the THz transmittance with and without pumping respectively. Fig.3(f) shows the modulation depth of bare Ge and GOG under the irradiation of femtosecond laser with a power of 250 mW. It should be noted that the maximum modulation depth of the GOG modulator can reach 62% at 0.38 THz. And in a frequency range from 0.2 to 0.7 THz, the modulation depth is over 50%, suggesting that GOG structure can be used as a spectrally wide-band modulator. It is worth mentioning that the pure Ge substrate also has notable modulation effects due to its high carrier mobility (typically 1 900 cm^2/Vs for holes, 3 900 cm^2/Vs for electrons). Compared with Ge, the modulation depth can be moderately enhanced(~10%) by introducing a monolayer graphene, which can be interpreted as the catalyst mechanism of graphene[22]. A heterostructure is formed by combining the graphene and Ge, where the electron-hole carriers occur when the 1 550 nm femtosecond laser excited. Most carries are generated in the depletion zone (Ge) and rapidly diffuse into the interface between graphene and Ge surface until an equilibrium. Since the mobility of graphene is up to ~20 000 cm^2/Vs[23], thus inducing an extra enhancement of conductivity and enabling an extra modulation depth enhancement. Therefore, the graphene helps Ge to generate more photo-carriers at the interface between Ge and the graphene, which works as catalyst to enhance the modulation depth.

4 Conclusions

In summary, we proposed and experimentally demonstrated a spectrally wide-band THz modulator. Based on monolayer graphene on germanium substrate structure, the modulator can be tuned by altering pump power of a 1 550 nm femtosecond laser. With the help of a home-made THz-TDS, we observed that in a frequency range from 0.2 to 1.5 THz, the average transmittance of THz decreases from 40% to 22% when the pump power is increased to 250 mW, while the absorption coefficient averaged increases from 19 to 44 cm^{-1}. The maximum modulation depth of the GOG modulator can reach 62% at 0.38 THz, and in a frequency range from 0.2 to 0.7 THz, the modulation depth is over 50%. Compared with bare Ge, the modulation depth can be moderately enhanced by introducing a monolayer graphene. This novel optically controlled graphene based THz modulator provides potential applications in THz communications and imaging.

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